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Unified description of scattering and propagation

FY15 Annual Report

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LONG-TERM GOALS

The long-term goal of the research is to increase the physical understanding of acoustic propagation and scattering in continental shelf and slope environments in the 50-4000 Hz band. This includes both the physics of the seabed and the coupling to physical mechanisms in the water column in complex range- and azimuth-dependent littoral waveguides. To achieve these goals it is necessary to understand the deterministic and non-deterministic components of both the theoretical description and the measurement and analysis parts of the problem.

OBJECTIVES

For FY15 there were two objectives. The first objective was to construct a theoretically consistent description of the effect of random fluctuations in the ocean on both forward and back-propagating acoustic field components. This work is complementary to the continuing investigation of the statistics of the mode intensity that result from scattering from a randomly rough seabed surface in a shallow water environment using a 2-way coupled mode methodology, however, is more general in that it can also address fluctuations in the water column. The second objective was to continue to develop a multistep maximum entropy (ME) methodology employed to simultaneously extract statistical information on both environmental parameters and source characteristics, such as the frequency dependent attenuation structure of the seabed and ship radiated sound pressure levels.

APPROACH

For the first objective, the approach develops integral statistical equations (as opposed to differential statistical equations) for both the forward and backward propagating average modal intensities. Previously Dozier and Tappert [1] introduced statistical equations for ocean acoustics, but only considered the forward field through second order in the coupling. A previous paper discussed generating statistics of the forward and back-propagating acoustic field by averaging field quantities

over multiple realizations of random perturbations of the environment and provided examples for a randomly rough seabed surface [2]. However, while such computations are exact up to finite differences and numerical quadrature, they are a highly inefficient way to explore field statistics. The new idea is to go forward with the Dozier and Tappert idea, but to use the standard mathematical physics approach where a 2-way differential operator is transformed into an integral or Green's function operator which in turn transforms a differential equation into an integral equation [3]. The statistical integral equations can then be solved by efficient existing numerical methods, such as those discussed in Ref. 2, especially in the weak coupling limit.

For the second objective a multi-step maximum entropy (ME) [4-5] method is applied for two case studies to infer the statistical properties of parameter values that describe the seabed. Of particular interest is the frequency dependence of the seabed attenuation, where the attenuation is expressed as $A(\mathrm{dB/m}) = \alpha\,(f/1000)^{\gamma}$. Understanding the frequency dependence of attenuation can then be related to physics-based models of the interaction of sound with a marine sediment. The technical challenge is the intrinsic ambiguity between source levels and geoacoustic parameters. The first case is for a sand sediment on the New Jersey continental shelf and is described in Ref. 6. The second case is for a thick mud sediment located in the Gulf of Mexico off the Texas coast. For both cases a conditional posterior probability distribution (PPD) is formed for a parameter space that includes both geoacoustic parameters and sound pressure level values for the emitting source.

WORK COMPLETED

The derivation of the statistical integral equations is complete, but the corresponding manuscript has not yet been submitted to the peer reviewed literature, but rather is in the preparation stage [7]. A description of the multistep maximum entropy method is now complete and has been applied to data collected during the ONR funded SW06 experiment for a coarse-grained sand sediment. A manuscript was prepared for JASA and is currently undergoing review [6]. As noted in Ref. 6 the multistep method should be applied to a mud like sediment for future work. Indeed preliminary results have now been obtained in the Gulf of Mexico with a sediment model characterized by multiple mud layers.

RESULTS

1. Statistical integral equations

If the acoustic field is split into forward and back-propagating field components as done in Ref. 8, then it is possible to derive statistical integral equations for the forward and backward propagating modal intensities and cross modal and forward and backward terms. An example of such an integral equation for the *n*th modal component is

$$< |\Psi_n^+|^2 > = < |\Theta_n^+|^2 > + \frac{1}{4\,k_n^2}\sum_p \{ < |\Psi_p^+|^2 > \; D_{npnp}(x) - \frac{2k_n}{k_p} < |\Psi_n^+|^2 > D_{nppn}(x) \}$$
$$+\text{terms involving} < \Psi_n^+ (\Psi_m^-)^* >$$

where

$$D_{abcd}(x) = \int_0^x dx' \, X_{abcd}(x')$$

and

$$X_{npmq}(x') = \int_0^\infty d\xi < C_{np}(x') \, C_{mq}(\xi) > \exp(i L_{qm}^* \xi).$$

Here the mode coupling operators for the *n*th and *p*th modes are denoted as C_{np} and $L_{qm} = k_q - k_m$ where k_m is the horizontal wavenumber eigenvalue for the *m*th mode and $\xi = x - x'$. Unlike the Dozier and Tappert statistical differential *master* equations for the forward field only, one has a set of integral *master* equations for both the forward- and back-propagating fields. Further, a Born series solution can be implemented in a rather straight forward manner, which has the advantage of providing physical insight into the contributions from the various order of terms and cross terms. In cases where a Born series fails to converge, one can transform the basic integral scattering equations into a bound state problem followed by an application of the Lanczos method [3].

2. Frequency dependence of seabed attenuation

The following results on the ship radiated noise are taken from Ref. 6.

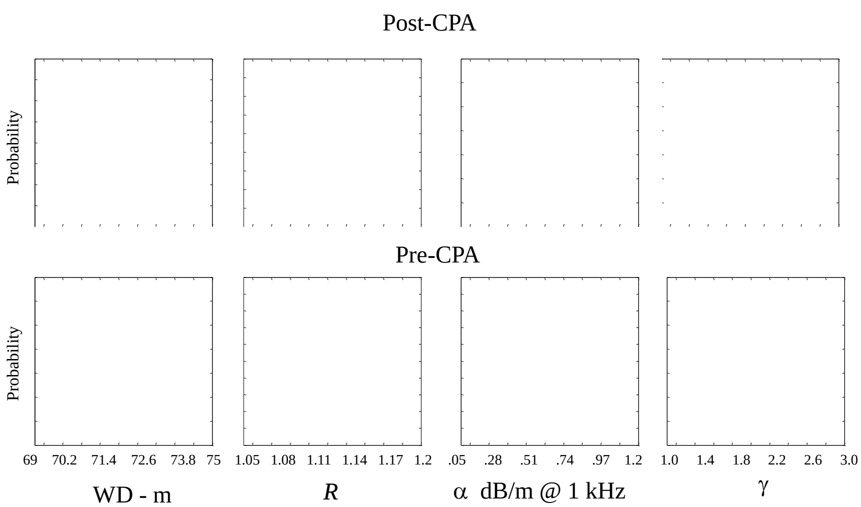

FIGURE 1: Marginal probability distributions of the water depth, R, α and γ for pre- and post-CPA track segments with posterior probability distribution constructed using 1-4 km and 60-360 Hz ship noise data.

Figure 1 shows the marginal probability distributions of the water depth (WD), the sound speed ratio R, α, and γ for pre- and post-CPA track segments using 1-4 km and 60-360 Hz ship noise data, where the attenuation has been expressed as $A(\text{dB/m}) = \alpha \, (f/1000)^\gamma$. The mean values for R for the pre- and post-CPA tracks are 1.137 and 1.165, respectively, corresponding to sediment sound speeds of 1694.5

and 1736.9 m/s, respectively, consistent with the known properties of the ridge of sand that the ship track is positioned. The standard deviations for *R* from processing the pre- and post-CPA tracks are 0.0186 and 0.0169, respectively. For both the pre- and post-CPA tracks, the marginal distributions for both α and γ are very broad.

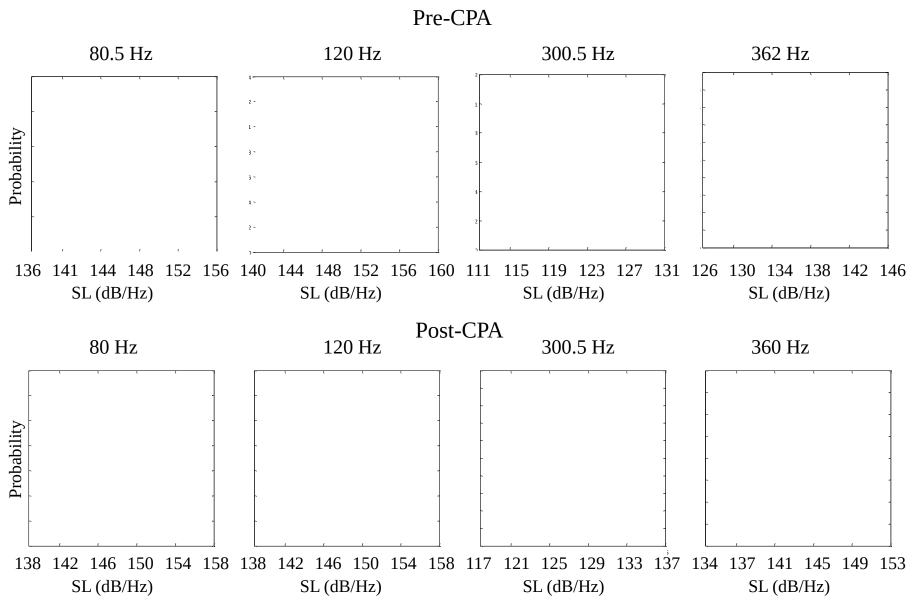

FIGURE 2: Selected marginal probability distributions for α and γ for pre- and post-CPA track segments with posterior probability distribution constructed using 1-4 km and 60-360 Hz ship noise data.

Figure 2 shows selected source level (SL_i) marginal distributions for pre- and post-CPA track segments using 1-4 km and 60-360 Hz ship noise data. Overall, one observes higher standard deviations for the bow aspect (pre-CPA) then for the stern aspect (post-CPA). It is not clear if the greater uncertainty of the SL_i for the bow aspect is related to model error associated with the environment or to model error associated with the assumption of constant SL_i over a specified range interval or both.

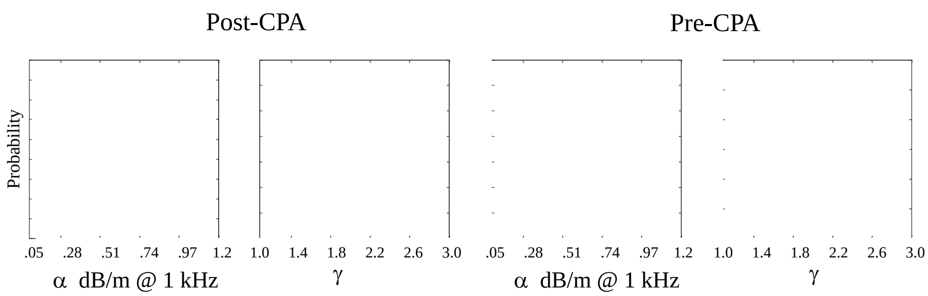

FIGURE 3: Marginal probability distributions for α and γ for pre- and post-CPA track segments with posterior probability distribution constructed using 1-10 km and 60-690 Hz ship noise data.

Figure 3 shows the marginal distributions for α and γ for both pre- and post-CPA portions of the track in the 60-690 Hz band and source-receiver range scales of 1-10 km. The marginal distributions

derived in Figs. 1-2 become the prior distributions for this second application of ME. For each application of ME it is important to note that a new likelihood function and thus PPD is computed. One now observes that for both the stern and bow aspect sections of the ship track both α and γ are resolved. The marginal distributions for γ generally have a peak structure around values consistent with what might be expected for a sediment that to first order is described by a Biot theory.

In addition to the ship radiated noise data, J-15-1 tow data with calibrated source levels were collected along the post-CPA portion of the ship track in the 50-700 Hz band. These data offered a means by which the results of using the ship radiated noise could be partially validated. The conditional PPD was constructed using the tow data with prior information provided by the marginal distributions for *R*, α, and γ that were previously determined from the ship radiated noise data. From this new PPD the marginal distributions for the J-15-1 source levels were determined. Table I shows the comparison between the average inferred levels and their standard deviations to the measured levels and their uncertainties. One observes *satisfactory* agreement, thus providing a partial means of validating the conditional PPD determined from the ship radiated noise.

f(Hz)	inferred dB/Line	measured dB/Line
53.0	150.5 ±3.0	152.9 ±2.6
103.0	155.0 ±3.0	155.9 ±2.6
203.0	152.0 ±3.2	153.9 ±2.6
253.0	151.3 ±3.1	150.8 ±2.6
403.0	150.1 ±2.2	149.0 ±2.6
503.0	146.7 ±2.1	146.8 ±2.6
702.25	145.2 ±2.3	149.7 ±2.6

Table I: Comparison of measured and inferred mean source levels from SW06 sand ridge experiment.

It was suggested in Ref. 6 that the multi-step ME method be tested for a mud sediment in anticipation of the Seabed Characterization Experiment 2017 location, reported to have a mud sediment [9]. It turns out that an acoustic experiment was preformed in a shallow water area in 1998 in the Gulf of Mexico in an area known to have a low speed mud layer. Work in this area goes back to Rubano [10]. Figure 4 shows the sediment layering reported by Berryhill [11] at the site where the measurements were made. There are three clay layers, each about 20 m in thickness. Over these layers is another 80 meters of soft consolidated sediments that have a small sand content.

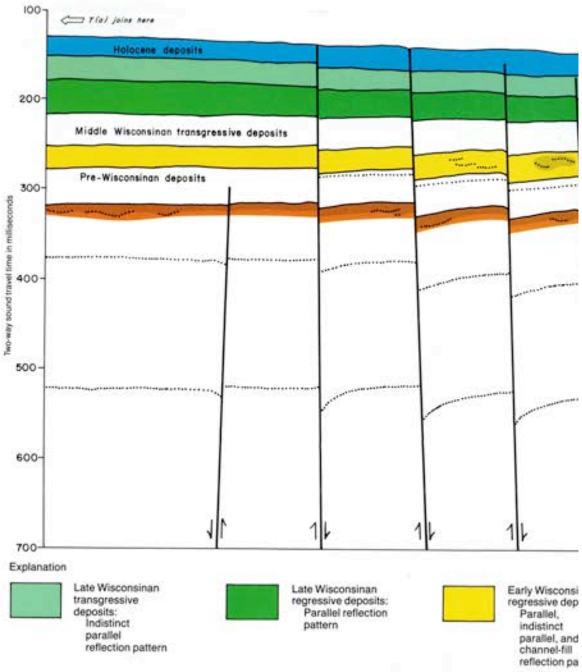

FIGURE 4: Sediment layering structure of Gulf of Mexico location provided courtesy Berryhill in Ref. 11.

Using the methods in Ref. 6, PPDs were constructed for recorded data on an HLA. The received acoustic data were generated by towing a J-15-1 at 30 m that emitted totals at 53, 103, 153, and 504 Hz. Figure 5 shows marginal probability distributions for the sound speed ratio at the water-sediment interface, the interface formed by the first and second sediment layer, and the interface formed by the second and third sediment layer. These sound speed ratios and their sediment thickness and sound speed gradients allow for a majority of the sediment penetrating energy to be returned to the water column via sediment refraction and reflection. Figure 6 is a comparison of the modeled transmission loss with maximum likelihood parameter values to the *measured transmission loss* (measured received levels minus the maximum likelihood source levels).

f(Hz)	inferred dB/Line	measured dB/Line
53.0	158.9 ±3.1	159 ±2.6
103.0	154.3.0 ±3.4	154.0 ±2.6
153.0	151.9 ±3.1	152.5 ±2.6
504.0	147.0 ±2.8	147.7 ±2.6

Table II: Comparison of measured and inferred mean source levels from Gulf of Mexico 98 experiment.

Table II shows the comparison of the measured and inferred mean source levels. Figure 6 implies that the sound speed structure of the seabed is accurately determined, however the α and γ values (not

shown here) are not well resolved, apparently as a result of insufficient bandwidth, number of frequency samples, or maximum source receiver range. However, as observed in Table II the average error of inferred mean and measured source levels is less than 1 dB. Like the SW06 case, this is another example that, even though the attenuation is poorly resolved as a result of insufficient bandwidth and/ or range scale of measured data, the mean source levels can still be accurately determined in a shallow water environment.

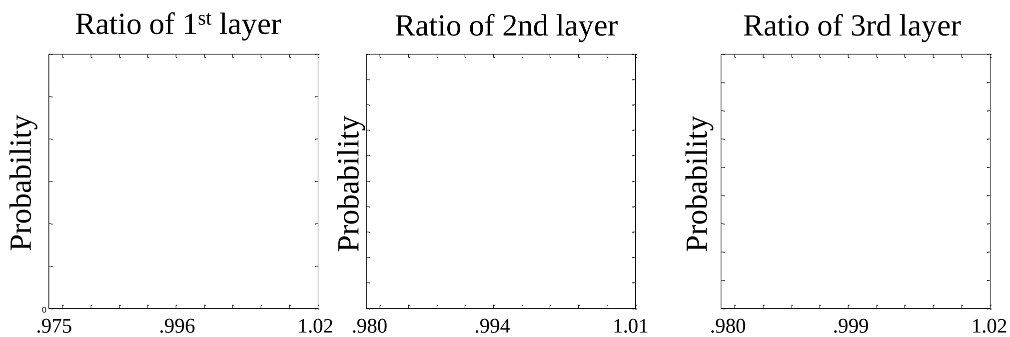

FIGURE 5: Marginal probability distributions of the sound speed ratios for the first three interfaces of a multi-layer sediment model based on the measurements in Fig. 4 for Gulf of Mexico data.

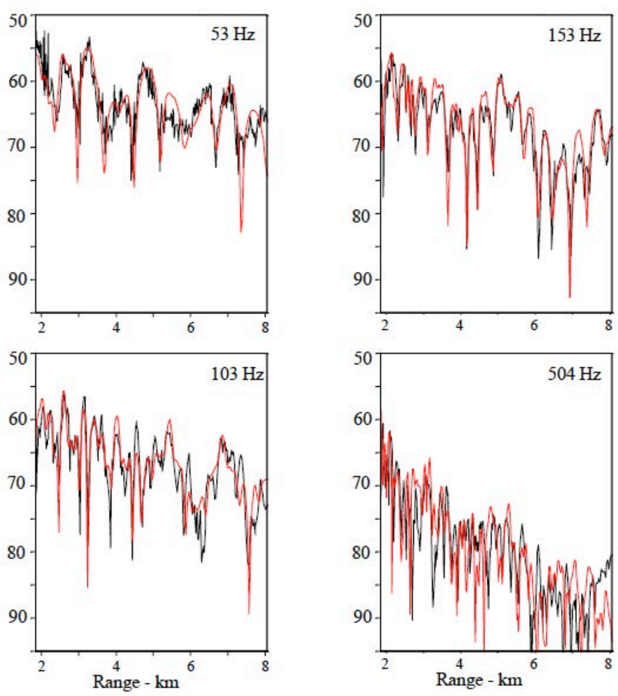

Figure 6: Comparison of modeled with measured TL derived from CW tow data recorded in Gulf of Mexico experiment. Red curves are modeled and black curves are derived from the measured received levels (RL) and the inversion solution for the source levels, where $TL_{measured} = SL_{inferred} - RL_{measured}$.

Thus in summary the analysis of data recorded at the Gulf of Mexico location has successfully established the statistics of the sediment sound speed structure for the multiple mud layers. The results have, as in Ref. 6, been partially validated by comparing inferred mean source levels with measured

values. However, unlike Ref. 6 the ability to resolve both α and γ has not been established. Current work is exploring data segments for the Gulf of Mexico data set with a larger bandwidth to address the ambiguity between α and γ. The hope is that these analyses will assist in determining optimal bandwidths and source-receiver range scales to resolve α and γ in the thin mud environment of Seabed Characterization 2017.

IMPACT/APPLICATIONS

One potential impact of this research is that the statistical inference of mud properties from the Gulf of Mexico data set may prove useful in the Seabed Characterization Experiment (SCE) 2017 off the New England shelf in an area characterized by mud sediments. A desired outcome for the application of the statistical integral equation study is to address the physics of propagation and scattering characterized by a high degree of non-deterministic physical properties in shallow seas at the mid frequencies.

TRANSITIONS

An interesting part of the single ship radiated noise study is that only two data samples were utilized to construct a conditional PPD. Even though the two data samples are when the source has mostly either a bow or a stern aspect relative to the acoustical array, a well-defined mathematical approach can still be defined that quantifies the statistics of both the environmental parameters and the aspect dependent source levels. Also, as seen, even though the attenuation may be poorly resolved as a result of insufficient bandwidth and/ or range scale of measured data, the mean source levels can be accurately determined in a shallow water environment. These observations may have possible implications on, for example, how one might design a system to monitor the aspect dependent source levels of merchant class ships for purposes of enforcing environmental compliance regulations.

The information theory aspect of this work, for example various entropy functionals and measures, is of general interest to various communities that deal with mining information from large data sets.

RELATED PROJECTS

Preparation for SBC 2017 and CANAPE 2016-2017 experiments.

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PUBLICATIONS for FY14

D. P. Knobles, “Maximum entropy inference of seabed attenuation parameters using ship radiated broadband noise,” to appear in J. Acoust. Soc. Am.